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1. What are the Hubble Space Telescope's most important contributions to the advancement of science? How important are those contributions compared to advancements expected from other astronomical programs at NASA, such as the James Webb Space Telescope to be launched in the next decade?

The Hubble Space Telescope (HST) was built to measure the age of the universe, explore the nature of distant galaxies, measure the mass of black holes, detect the dark matter between galaxies, study the nature of stars in the Milky Way and neighboring galaxies and even planets in our own solar system. It made tremendous progress on all of these goals within a few years of launch. More importantly, Hubble opened up entirely new fields of research not included in its initial goals. Hubble looked back close to the time of creation by observing the assembly of the first galaxies when the universe was only 7% of its present age, it confirmed that the universe is accelerating, one of the most profound discoveries in 100 years, it obtained images of young solar systems around other stars before planets had formed, it detected extra-solar planetary systems and even measured the atmospheric chemistry of one extra-solar planet. Most recently, Hubble helped discover the most distant object in the Solar System.

The Hubble Space Telescope has far outpaced everyone's early expectations of success. An essential element of that broad success is NASA's ability to upgrade the scientific instruments with modern technology through servicing by shuttle astronauts. Hubble is currently poised to address several of the most important problems in astrophysics, indeed, in all of science over the next 5 to 10 years, if new instruments are installed on another servicing mission. Two of these problems, the nature of dark energy that powers the acceleration of the universe and the properties of extrasolar planetary systems, were not even active topics of observational research when Hubble was designed in the 1980's and therefore were not part of Hubble's mission goals. Hubble's enormous impact in helping us uncover the secrets of the cosmos has come about because it is a multi-purpose observatory with observational powers greatly exceeding those required for a single problem or set of problems that the mission designers could divine before it was launched.

Hubble's discoveries drove it to the top of the nation's most productive scientific facilities. By the metrics we use to measure scientific success, Hubble is number one. It annually produces more scientific papers that collectively receive more citations in the scientific literature than any other astronomical observatory or instrument. The widely used Davidson Science News metric, NASA's own measure of the relative successes of its different missions, ranked Hubble number one in science impact for the last 10 years. In 2004, the most recent year for which this metric is available, Hubble had almost twice as many important discoveries as the next highest producer among NASA missions, and it was the only one of the top 25 most productive missions to gain discovery points. It shows no signs of slowing down.

Just as important as Hubble's scientific contributions is its impact on education and public awareness of science. Its pictures reveal the complex structure of galaxies and nebulae. The vivid colors and rich information content of its images with unparalleled resolution captivate millions of Americans and people around the world each year. Hubble's pictures make even esoteric concepts about the universe accessible to schoolchildren. One of my first memories of coming to Baltimore six years ago was going to Dumbarton Middle School on parent visiting night where both my children enrolled. I saw Hubble pictures in every classroom on my kids' schedule, including English, social studies, and health in addition to their science classrooms. Hubble has been one of our most important tools to excite children about science at a time when the need for a technically astute workforce is more important than ever to our economic future.

At present, there is no other mission planned or under construction to duplicate Hubble's capabilities and major strengths. The James Webb Space Telescope (JWST) is designed to have the same angular resolution – or sharpness of image – as Hubble covering a different wavelength band and with greater light gathering power. The tremendous advances enabled by Hubble have driven the scientific community to pose questions that were not even imagined a decade ago, but now form the basis for the JWST mission.

The James Webb Space Telescope complements the Hubble Space Telescope as part of a continuous, balanced program to study the universe with flagship observatories. Hubble's sensitivity to ultraviolet and visual light and its high performance now make it an enormous value to astronomy. JWST's coverage of infrared wavelengths and large collecting area will make it an essential asset when it is launched. JWST's anticipated success in the future guarantees its high priority for the next decade.

Because of the strong scientific relationship between HST and JWST, the original plan envisioned by the scientific community would have allowed an overlap of several years to accomplish an orderly transition of observing programs. We now realize that HST's future potential is even more important than previously thought owing to new discoveries about the universe and its constituents from HST and other facilities. It is essential to complete the HST mission and let it fulfill its scientific potential in preparation for the era that will be dominated by JWST, the Terrestrial Planet Finder, and other astronomical missions in the NASA Strategic Plan.

2. Should a Hubble servicing mission be a higher priority for funding than other astronomical programs at NASA?

Setting priorities for astronomical programs at NASA is normally done in three ways. The first is the National Academy of Sciences' Decadal Surveys done every ten years to provide a long-term look especially at large missions. The most recent Decadal Survey ("Astronomy and Astrophysics in the New Millenium 2001") considered NASA's plan to service Hubble with SM4 and operate it until the end of the decade, 2010. The survey committee believed that was a good plan and one that they supported even with the demands of competing new instruments such as the James Webb Space Telescope.

The second is to have special "blue ribbon" committees examine particular issues or proposals in between the Decadal surveys. These committees draw their members from the elite of the scientific establishment who are not direct beneficiaries of the missions under review. Two such committees recently reviewed Hubble: the Bahcall committee (chartered by NASA's Office of

Space Science) in August 2003 and the Lanzerotti committee (chartered by the National Academy of Sciences) in December 2004 ("Assessment of Options for Extending the Life of the Hubble Space Telescope (2005)"). Both committees had winners of the most prestigious research prizes in science, including the Nobel prize, and the latter committee also had a large number of distinguished engineers, astronauts, and former senior managers from the aerospace industry, military, and NASA, including an ex-NASA Administrator. Both committees gave a strong endorsement to the fifth Hubble servicing mission, SM4. The Lanzerotti committee stated that the future scientific returns from Hubble are likely to be as important as its past discoveries. No other NASA mission has been so extensively reviewed by independent committees of such high capability and prestige.

The third is NASA's own advisory system. In that system, representatives of different subfields of astronomy advise NASA on the relative merits or their projects. The most recent resolution about SM4 came from the Space Science Advisory Committee (SScAC) meeting of November 2003, in which the committee reaffirmed that continuing Hubble's success in this decade with SM4 is essential to a balanced program of high-profile astronomical research..

3. What are the comparative strengths and weaknesses of a shuttle servicing mission, a robotic servicing mission, and a mission to fly elements of a Hubble servicing mission rehosted on a new telescope?

The Lanzerotti report concludes that a shuttle servicing mission, SM4, would give us the most scientific capability in the shortest amount of time at the lowest risk among the three options. Time is an important advantage that is often neglected as a factor in scientific importance. SM4 gives us two new instruments in addition to Hubble's current suite in about 3 years, continuing to provide overlap with NASA's other Great Observatories, Spitzer and Chandra, for example. It would extend Hubble's lifetime another 4 to 6 years (likely overlapping early operations of JWST), and it would provide us with the possibility of fixing the currently inoperative Space Telescope Imaging Spectrograph to further enhance Hubble's scientific power. Since the instruments and other components needed to service Hubble are nearly ready for flight, the costs to the science budget, *exclusive of shuttle infrastructure costs*, are likely to be relatively low and predictable compared to the four previous servicing missions. The chances of mission success are very high, as the Lanzerotti report emphasized, consistent with four successful servicing missions in which 18 consecutive spacewalks achieved all of their objectives.

A successful robotic servicing mission could give us much of the same new scientific capability as SM4 depending on how it is planned, but somewhat later in time. It is unclear how the cost of a robotic servicing mission would be shared between the science budget and the budget for the new exploration initiative. It is important to distinguish between a robotic mission that has the capability to install the new instruments and upgrade Hubble's batteries and gyroscopes from one that simply de-orbits the telescope. NASA has committed to a de-orbit mission that by itself would produce no new science. In these remarks, I refer to a mission that would upgrade Hubble's scientific instruments and increase its lifetime as well as install a de-orbit module.

The robotic mission would be able to install new instruments, batteries and gyroscopes, although it would not be able to repair some of the infrastructure items normally done by astronauts. Thus, Hubble's lifetime following a robotic mission is likely to be shorter than that following SM4, although an exact number is a matter of debate. The chances of mission success with robots are likely to be smaller than for SM4, simply because robotic servicing is untested and without the flexibility that humans bring to any task with unforeseen problems.

On the other hand, a robotic servicing mission would demonstrate new technology that could be important to NASA's new exploration initiative and to future scientific facilities that are not accessible to humans. Thus, the potentially higher cost and risk would be offset by the future potential of using this technology for other missions. Indeed a whole generation of future scientific missions might be enabled by a robotic capability initiated in this decade. The robotic option also has the advantage of providing Hubble with the de-orbit module capability it needs to be safely de-orbited at the end of its life.

The third option, re-hosting, could recover some of the science capabilities of a fully serviced Hubble. I assume here that re-host means building an equivalent sized telescope to Hubble containing the two new instruments already built, the Cosmic Origins Spectrograph (COS) and the Wide Field Camera 3 (WFC3) as assumed in the Aerospace Corporation study of alternatives to Hubble servicing. Such a telescope will deliver less scientific capability at a much later time with higher risk than servicing Hubble. The new telescope would have to have a 2.4m mirror with a pointing stability of a few milliseconds of arc, the most challenging part of Hubble's construction. That mission would be launched in approximately 8 years, according to the Aerospace study. Thus, we would have a Hubble Lite with two working instruments in 2013 rather than a full Hubble with four to five working instruments (depending on STIS) in 2007 or 2008.

Time is an important element in this case, because Hubble Lite would become available after the currently planned launch date of JWST in 2011. JWST's infrared capabilities will supercede those of WFC3. The lack of two of Hubble's current instruments, the Advanced Camera for Surveys (ACS) and Near Infrared Camera and Multi-Object Spectrometer (NICMOS) means that two of the four most compelling future science projects with Hubble that I discussed with the Lanzerotti committee would be impossible. My understanding from the Aerospace study is that even Hubble Lite would cost the science budget between $1.5 and $2 billion, not unreasonable considering the cost to build Hubble in the first place, but certainly higher than typical costs of a shuttle servicing mission, less than $500 million. The chances of mission success would be lower than those for SM4, simply because of the infant mortality risk for all new space missions.

It is, of course, always possible to propose a re-host mission with new capabilities that Hubble does not have, such as the HOP telescope consortium proposes. Such a mission would be scientifically attractive by providing even more capability than a Hubble Lite. Depending on the precise proposal and configuration, it could be designed to address specific science problems, such as the dark energy problem. There are other mission proposals to provide new telescopes with new capabilities that would have to be weighed against one another, since none have yet undergone the extensive reviews that the Hubble program has. It would also not have the public recognition that has made Hubble so beneficial to education and public outreach. I assume that any telescope with more capability than Hubble Lite would also be more expensive and carry more development risk than either a re-host mission or SM4.

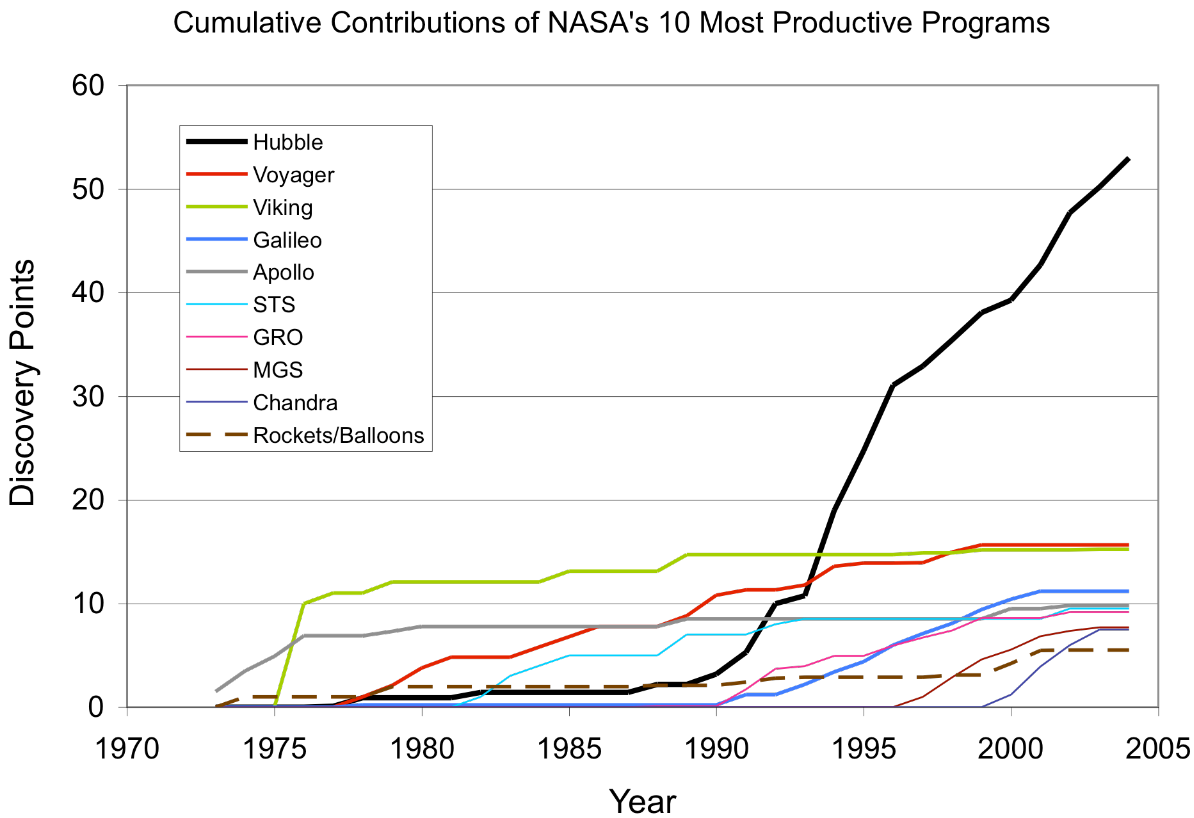

Figure 1: This chart plots the Davidson Science News Metric showing the cumulative discoveries from NASA's 10 most productive missions over time. Of these missions, only Hubble, Chandra, and Rockets/Balloons are still active.

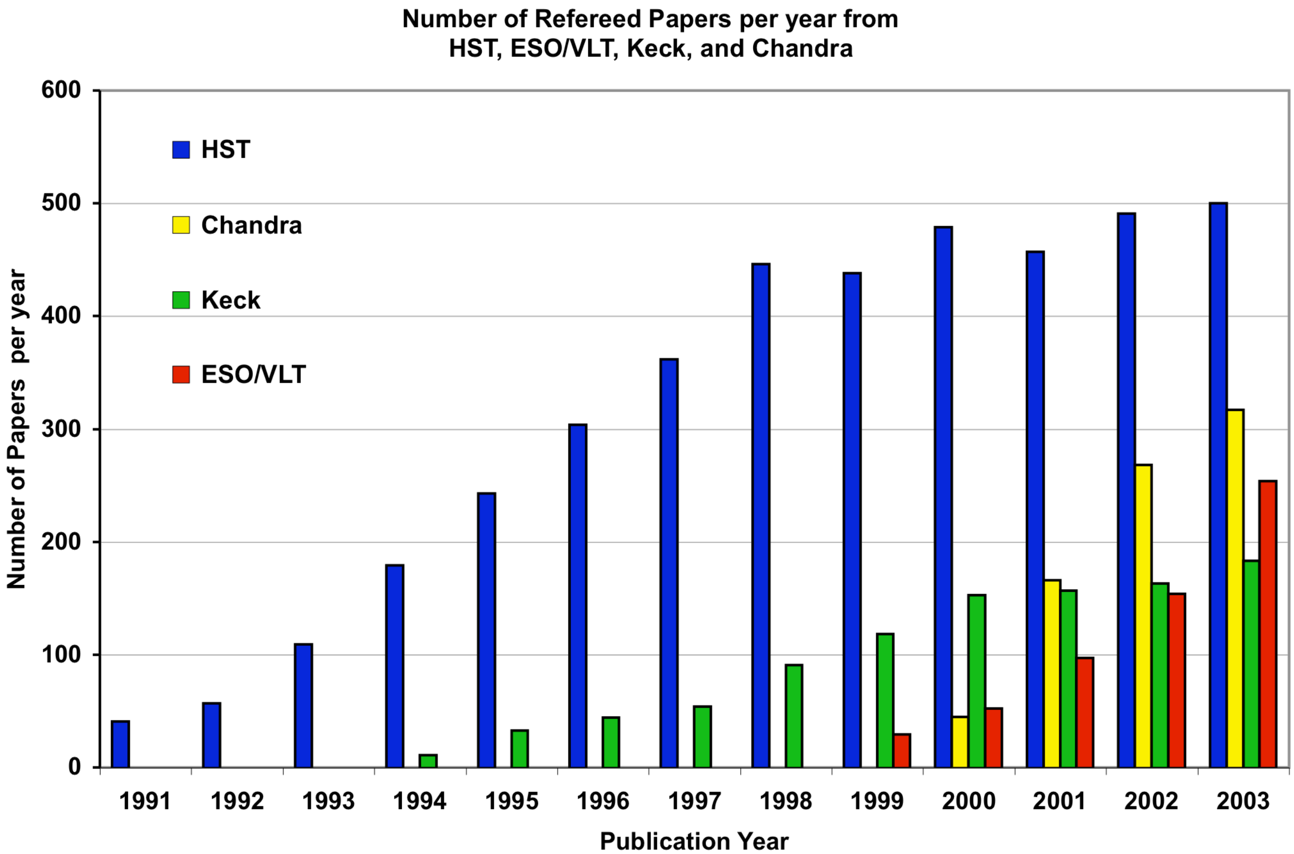

Figure 2: This chart compares the number of refereed papers per year published from four of the world's most productive observatories: NASA's Hubble and Chandra observatories and the ground-based Keck and VLT observatories.